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SOME ASPECTS OF SENSORY ACTIVITY AS APPLIED TO PROBLEMS IN SPACE PHYSIOLOGY

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Translation of "Nekotoryye voprosy deyatel'nosti sensornykh sistem primenitel'no k zadacham kosmicheskoy fiziologii"

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There is no doubt that the normal functioning of the sensory systems is a major condition for effective adaptation to the environment in general and to the complex ambient medium of space in particular. In the latter, the interaction of man and automatic devices, i.e., the "man-machine" situation, is of utmost importance. Almost freed from the need to perform physical work, the astronaut must solve problems connected with controlling the spacecraft, carry out a variety of observations, and make rapid and correct decisions. All these tasks are associated with the acquisition and processing of information, the most important phase of which is effective coding and coordination of machine characteristics with the "capacity" of the astronaut-operator.

In accordance with this general problem, our report will deal /2 with several important matters relating to the obtaining and processing of information and to the recognition of sensory images. These matters naturally do not exhaust the problem, but we shall concentrate on them because of our experience in the field. The first pertains to the problems of orientation in space and it has been studied in experiments on animals (V. A. Kislyakov et al.). The second involves the recognition of visual images (V. D. Glezer et al.). The third deals with the recognition of speech sounds (V. A. Kozhevnikov, L. A. Chistovich, et al.

*Numbers given in the margin indicate the pagination in the original foreign text.

The second and third subjects are based on data obtained from observations on human beings. Our solutions are tentative and subject to further investigation.

* * *

We shall begin by discussing the nature of the general scheme that we have adopted for use in solving the problems. It is an acknowledged fact that the question of the most efficient distribution of functions as between man and machines cannot be answered empirically or on the basis of common sense. It requires a deep theoretical study of engineering psychology. A substantial mass of information has accumulated in recent years on certain parameters of the man-operator. However, the data apply mainly to elementary functions - work at the control panel, keeping an object under observation, etc. Much less attention has been paid to the problems confronting the commander of the spacecraft /3 and observer-investigator when the volume of information may be very large and errors in reaching a decision likely to be disastrous. The place and role of the astronaut in the overall system of processing information and control are schematically shown in Fig. 1.

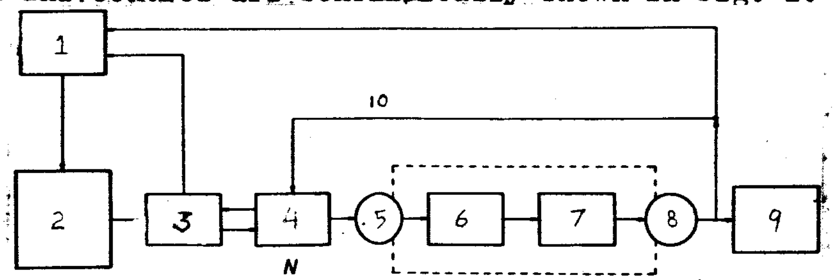

Fig. 1. Main routes for information transmission in a "man-machine" system.

1 - Control of spacecraft; 2 - Spacecraft and ambient medium; 3 - Automatic description and evaluation of situation; 4 - Description of situation for man; 5 - Input; 6 - Analysis of situation; 7 - Reaching a decision; 8 - Output; 9 - Storage of information; 10 - Inquiry for additional information

The astronaut characteristically deals not only with the data obtained from direct observation of a situation, but with the results of automatic processing and evaluation of information partly performed by instruments. The signals in unit N (Fig. 1), which describe situations in symbolic and abbreviated form, represent input information for the astronaut. Another feature of the operator's work is that his actions are not ordinary direct actions with objects but control signals which must be recognized, integrated by the automatic control system, and co-ordinated with other signals circulating in the system.

A major task of engineering psychology is to select the optimal system of signals for delivering information to the operator and the optimal system of actions by which the operator transmits information to the machines.

The operations involved in the processing of information by man (the part of the diagram enclosed in broken lines in Fig. 1) clearly belong to the sphere of thought. Although we do not as yet know what /4 intellectual operations actually are, we nevertheless must assume that they are performed in response to certain signals or symbols. It is logically necessary to assume that these symbols form an ordered set, a dictionary of thought, and that there are, in addition, definite rules governing the analysis and synthesis of groups (series) of symbols. The dictionary and rules together make up what may be called the language of thought.

Assuming then the language of thought, we must naturally add to the scheme for the processing of information by man (Fig. 1) at least two more units, i.e., an input for translation from the language of the signals received into the language of thought and an output for translation from the language of thought into the language of actions. The capacity of the system will naturally be greater, the simpler is the translation from the language of thought into the language of actions. It would be optimal if the two languages coincided. There is a prevalent view in psychological literature that the thinking of adult human beings is largely verbal and that it also consists of operations with visual images. Deeming these assumptions highly plausible, we advanced the hypothesis that a combination of oral and visual communications is the best means of providing the operator with "input" data and that his oral instructions, possibly combined with some simple motor acts, are the best control signals. 15

In pursuing this general scheme, we shall consider the three problems in order. Limitations of time prevent us from setting forth all of the purely factual material in our report. We shall also be very sparing in our description of the methods we used and in reviewing the literature. Attention will be focused mainly on the application of the results to the practical needs of space flight.

Two kinds of phenomena in the body originating from the receptors have several features in common. These phenomena arise after exposure to acceleration or when orienting points shift in the field of view of man and animals. They include vestibular and optokinetic reactions. In a high-altitude or space flight, changes in afferent signals from the receptors give rise to optokinetic and vestibular stimuli, which create discomfort, impair spatial orientation, and engender illusions that make the astronaut less efficient in performing the delicate operations involved in receiving, processing, and transmitting information.

Elucidation of the mechanisms of the above-mentioned disturbances through experiments on animals is essential for aerospace medicine.

The following illusions are known to arise in man after vestibular stimulation:

(1) Illusion that the body is moving in the opposite direction after rotation ceases. /6

(2) Oculogyral illusion - apparent movement of the observed orienting point after the semicircular canals are subjected to angular accelerations (Grable).

(3) Oculogravitational illusion - apparent revolution of an observed orienting point and its displacement vertically after the otoliths are subjected to centrifugal forces (Grable).

Similar illusions may occur after optokinetic stimulation.

(1) When a human being is inside a large revolving cylinder with stripes, he gets the sensation that his body is moving in the opposite direction while the cyclinder seems to be motionless (Kislyakov).

(2) Reversive rotation illusion, which arises when the eye moves from revolving stripes to motionless ones which seem to be moving in the opposite direction (Miller).

(3) Reversive postoptokinetic illusion - apparent movement in the opposite direction of a light spot against a dark background following optokinetic stimulation (Miller).

(4) Illusion of a light spot falling, which arises when the stripes move vertically from top to bottom (Miller).

The illusions of human beings observed in the laboratory also arise during actual flights, where, owing to the complex conditions, they result in impaired spatial orientation. Consequently, it was necessary to have an analog of illusions in animals in order to be able to study the nerve mechanisms responsible. Optokinetic stimulation was chosen for this purpose.

We obtained in our experiments (Kislyakov et al., 1963) a new form of nystagmus called "reversive postoptokinetic nystagmus" (RPN). RPN /7 occurs in rabbits after prolonged optokinetic stimulation and it is in a direction opposite to that of the preceding optokinetic nystagmus (OKN), and it lasts for 20 minutes or more (Fig. 2). The intensity is greatest during the first 10-15 minutes.

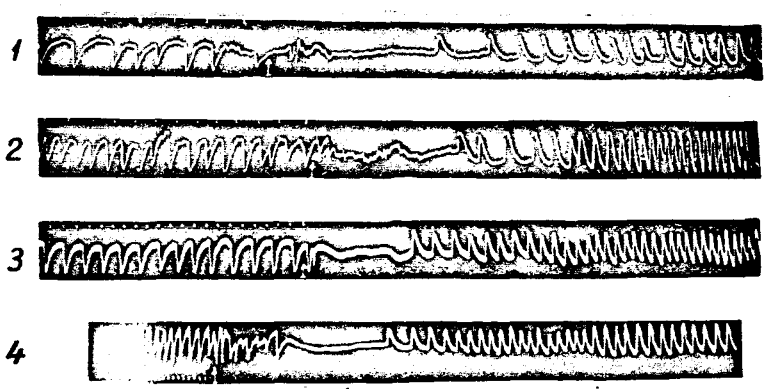

Fig. 2. Electronystagmograms of OKN and RPN at various velocities of rotation of the cylinder: 1 rpm (1); 1.8 rpm (2); 2.5 rpm (3); 6 rpm (4).

The arrows designate the time the dark screen was set up; dots - mark of stripes; calibration - 200 μv; time - 1 sec.

An essential condition for RPN to appear is the exclusion of visual stimuli (darkening of the experimental room or setting up of a dark screen). Incidentally, Miller's optokinetic illusions were strongest when illumination was reduced.

We regard RPN in rabbits as an analog of the illusory optokinetic reactions manifested in the objective indicator of nystagmus. A change in the direction of nystagmus in RPN can be viewed as a manifestation of the induction processes that arise in the nerve centers after OKN is halted. Consequently, during OKN conditions are created in the nerve centers for development of the process in the opposite direction. Special experiments with a 30-60 minute lag in darkening after the cessation of optokinetic stimulation revealed that RPN occurs even after this long interval of time. The delayed RPN is indicative of the prolonged circulation of trace excitation in the nerve structures without reaching the effectors, i.e., the motor neurons of the eye muscles. This suggests that the circulation of trace excitation occurs in the sensory rather than motor region of the brain. Based on a phenomenological study of RPN, we have tentatively concluded that illusory optokinetic reactions derive from trace excitation and that there are summation and induction processes in the nervous system. Our experiments show that traces of previous optokinetic stimuli may persist in the central nervous system for a long time and that they may appear unexpectedly in the form of disagreeable reactions when visual stimuli are restricted.

Optokinetic stimuli with their changing frequency parameters are an inseparable companion of man as he travels in all kinds of modern 18
ground, water, air, and space vehicles. This brings up the question of the significance of the various links in the visual system in adjusting the parameters of OKN to those of optokinetic stimulation. RPN proved to be an important criterion for assessing the mechanisms of transformation of the OKN rhythm

in relation to the frequency with which optokinetic stimuli succeed one another in a unit of time. Data on the frequency of OKN and RPN are presented in a generalized form in Fig. 3. The frequency of OKN and RPN is laid off on the ordinate and it shows the number of nystagmic oscillations per minute. The velocity of rotation of the cylinder with stripes (rpm) is laid off on the abscissa with an indication of the number of stripes entering the rabbit's visual field in 1 minute. The solid line in the graph reflects the frequency of OKN; the broken line, the frequency of RPN in the same experiments. Each dot is based on 20-40 experiments
on 4-6 rabbits. Consequently, one can analyze from these curves the /19
dynamics of the frequency of RPN in relation to the preceding OKN. It is evident from the figure that the rhythm of RPN reaches a peak before that of OKN. This reflects the relative independence of the RPN rhythm from that of the preceding OKN. The maximum frequency of RPN is virtually equal to that of OKN. RPN is essentially a manifestation of the prolonged cyclic activity of the nystagmogenic nerve centers, and its maximum rhythm reflects the frequency with which these centers may generate nystagmus. This suggests that the appearance of the plateau on the OKN frequency curve depended on the resolving power of the nerve centers responsible for nystagmus. Based on information concerning the frequency and velocity of the movement of stripes coming from the retina (the nerve centers) controlled the increase in frequency of OKN within a given range of cylinder rotation frequencies (1-6 rpm) and then maintained a stable OKN frequency (6-15 rpm).

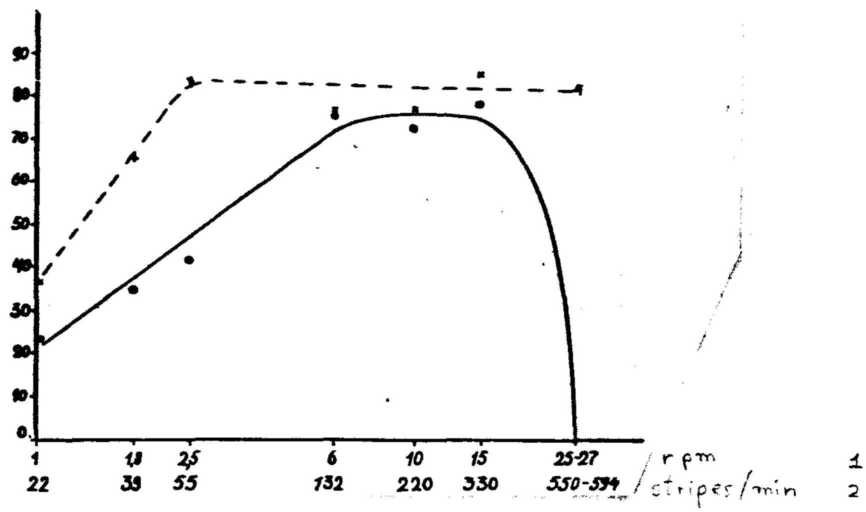

Fig. 3. Change in frequency of OKN (solid line) and RPN (broken line) with different frequency of optokinetic stimulation.

Symbols: abscissa - velocity of rotation of optokinetic cylinder in rpm; ordinate - frequency of OKN and RPN in nystagmic oscillations per minute.
1 - rpm; 2 - stripes/min

The cessation of OKN was thought to be due to achievement of a critical frequency of coalescence of flashes at which the retina cannot distinguish stripes or groups of stripes discretely. However, the existence of another indicator in the form of RPN enabled us to interpret this fact in a different way. Actually, in this series of experiments too, all the animals developed RPN after vision was excluded. This implied that the critical frequency of coalescence of moving stripes is higher and was not achieved even at a velocity of 25-27 rpm (550-594 stripes/min). Cessation of OKN at this velocity and rate of movement of the stripes was effected by the oculomotor apparatus for which these were the critical parameters of optokinetic stimulation. The eye in discriminating discfetely the black stripes and white intervals could not react to the movement with nystagmic oscillations.

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The phenomenon of RPN as a manifestation of trace automatic activity of the nerve centers was used to analyze the mechanism of transformation of the frequency of OKN with a different frequency of movement of the stripes. This made it possible to examine the role of the nerve centers, oculomotor apparatus, and retina in the transformation of the OKN rhythm.

Let us now consider the second problem.

The receptive fields of the retina perform several operations in transforming visual information: storage and recovery of signals from noises, change in sensitivity to resolving power (i.e., increase in visual acuity with illumination), and impairment of correlation of signals in time and space (obtaining responses only to change in the light signal, distinguishing of the contours of an image). With low levels of illumination the rods, which sum the signals over a large area, come into operation. This ensures high photosensitivity, but visual acuity is not great. When there is more light, the smaller cone fields begin to function. The effective size of the cone fields diminishes as the amount of illumination increases due to the development of inhibition, which functionally cuts off the peripheral receptor fields. With low illumination, a great many receptors are switched to a single ganglion cell, all the inputs /11 are positive, and excitation from the incident light is summed over a large area (Fig. 4a). With a high level of illumination, each receptor has its own output, the peripheral receptors send inhibitory signals to the output cells, and the resolving power of the system is great, but sensitivity is low (an insignificant fact because there is enough light). (Fig. 4 b). In going from one illumination to another (as shown in the top curve, Fig. 4 c), the receptive field is rearranged (shown below). Meanwhile there is an impulse response, which lasts until excitation in the field is balanced by reactive inhibition. Finally, in the region of the decreased illumination the receptive fields accentuate the contours of the image. If the distribution of light on the retina is like that shown by the top curve in Fig. 4 d, the signals proceeding from the receptive fields at the place of the decreased illumination will not reflect its true distribution, as shown by the bottom curve, and the decrease in illumination will be accentuated. The next step in processing information is carried out by receptive fields of a higher order. /12

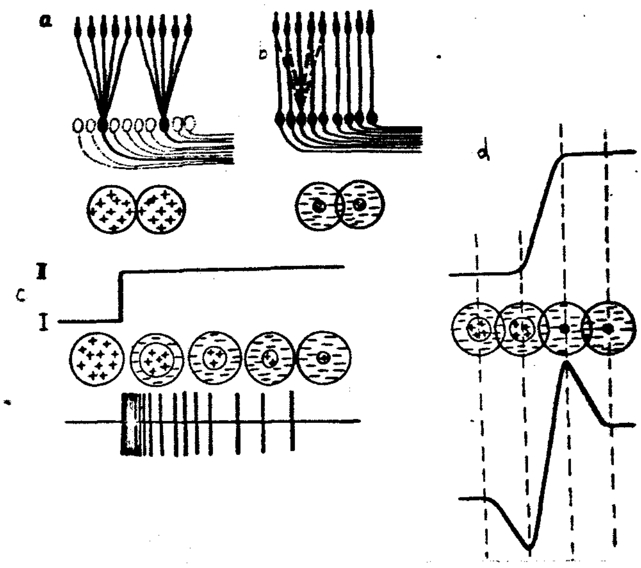

Fig. 4. Diagram of operation of the receptive fields of the retina. Explanation in the text.

A recent mass of data show that the visual analyzer has several channels or systems, each of which describes some property of the image. The following have been provisionally identified: a system of coding signal intensity, a system of coding light, a system of distinguishing elements of form, and a system of detecting movements. As a result, the image is represented by a set of signals which describe it in a different form from that projected on the receptors of the retina.

The purpose of the mechanisms of primary processing of information is to remove redundancy in the communications transmitted through the visual system. This redundancy is due to the statistical properties of the objects of the outside world and not to the set of visual images which the individual has learned. Therefore, the primary processing of information is performed by determined mechanisms genetically fixed in the course of evolution. We carried out experiments that enabled us to find the psychophysiological expression of these mechanisms. The experiments revealed the time needed to recognize a given image. An image was presented for a prescribed period of time, then replaced by another "obliterating" image to mask the first. Thus, after presentation of the test image, the processing of information was abruptly halted by switching the visual system to a new task. In Fig. 5, the time that the image was shown is laid off on the abscissa; the average amount of information obtained by the observer during a single presentation is laid off on the ordinate. The observer was trained to recognizes a particular set of images. The broken lines indicate the results of the experiments when the sets consisted of segments of straight lines oriented in various ways; the solid line, when the sets consisted of pictures of ordinary objects in outline. The data were obtained after the subject was completely trained to recognize the images of a particular set. L13

In recognizing 4 or 8 variously oriented lines, the time of presentation does not determine the amount of information obtained. The in the visual system due to learning.

If such images are presented for a short time, insufficient for infallible recognition, the average amount of information obtained by the observer during the given period of time is the same whether 3, 5, or 10 figures are recognized and it is directly proportional to the time of presentation of the images (as shown in Fig. 5 by the solid lines). The slope of the solid line shows the amount of information obtained /14 in a unit of time, i.e., the capacity of the visual system. Calculation of the capacity from the rate of recognition of solitary images of objects in outline yields values of 35-110 binary digits per second among different observers (generally about 50-70 binits/sec).

On the basis of these and other investigations, the process of visual recognition can be conceived of in the following way. After primary transformation of visual information in the retina, the higher portions of the visual analyzer distinguish the elementary characteristics of the image. The mechanisms of distinguishing the elementary characteristics operate in accordance with standard subprograms. Thus, the time required to detect the elementary characteristics does not depend on the amount of information transmitted by them. From the elementary characteristics complex characteristics are formed in the process of learning that are invariant in relation to such transformations of the image as displacement in the visual field, turning within certain limits, change in size, etc.

Recognition of an image as a generalization is achieved by successive analysis of complex characteristics.

What are the implications of these investigations for space physiologists? The amount of information that the visual system can process in a unit of time under various conditions and with different parameters of visual stimulation must be determined in order to be able to efficiently design devices for supplying visual signals (panels) /15 when man is a link in the control system. This is especially important in space flight when man must assess situations correctly and quickly. Our investigations are also of value in creating devices for transmitting visual signals. And, finally, they have bionic significance in designing devices for automatic recognition of images on new principles. Research on the receptive fields of the retina may be helpful in setting up a system to provide for simultaneous processing of information (unlike the successive processing ordinarily used in television systems). Analysis of elementary characteristics reveals that it is more efficient to feed into a teaching system for recognition signals produced by standard subprograms organized like cortical receptive fields rather than signals coming from receptors, as is done in the perceptron.

The principle of successive recognition may have still another application. The current programs of recognition and models of sensing devices are designed for the presentation of single images. A combination of several images to be recognized separately is something new and unfamiliar for them. The construction of a system that could find both the familiar and the unfamiliar through recognition of one thing while ignoring all the others would be quite feasible due to successive analysis.

Let us now examine the third and last problem. /16

There are two aspects to consider in a man-machine-man system: man as a receiver of oral information and man as a source of oral information. It is convenient to distinguish between two kinds of information in developing methods of communicating essential information to the operator. One may be defined as information about the important parameters of an actual situation without an evaluation of it. Each parameter can be regarded as a continuous variable. The aim of the operator is to evaluate the situation from the observable values of the parameters. The other type is information about decisions. A very simple example of a decision is switching on the signal of attention or alarm when the values of an important parameter have gone beyond permissible limits. It is obviously better here to use sound signals because they can be perceived by the operator wherever he may be in the cabin. Serious difficulties arise as soon as it is necessary to transmit by sound signals a large volume of information. The accuracy of absolute discrimination of artificial sound signals is known to be very low. Studies carried out in the Institute of Physiology have shown that, in addition, the time of reaction to sound when multiple choices are possible increases greatly. One solution is to use either oral communications (optimum situation) or speech-like artificial signals. /17

Fig. 6 shows the possibility of recognizing 3-element sound sequences consisting of vowels (curve 1) or pure tones (curve 2). The duration of the elements of the sequence is laid off on the abscissa; the amount of information received, on the ordinate. It can be seen that the vowel sequences are fairly well distinguished by man when the duration of each vowel is 100-200 msec. Tonal sequences of similar duration cannot be distinguished at all. Satisfactory discrimination wider the choice, the more information the observer obtains in the same length of time. This is to be expected if a straight line is detected by the mechanisms of the receptive field operating in accordance with a standard program; the time required to detect such a configuration is determined wholly by the conditions under which the signal was formed. This is recognition from a prepared model, from a comparison with a stored standard. The detection of very simple configurations like the segment of a straight line of a given orientation may be regarded as the identification of the elementary characteristics of form.

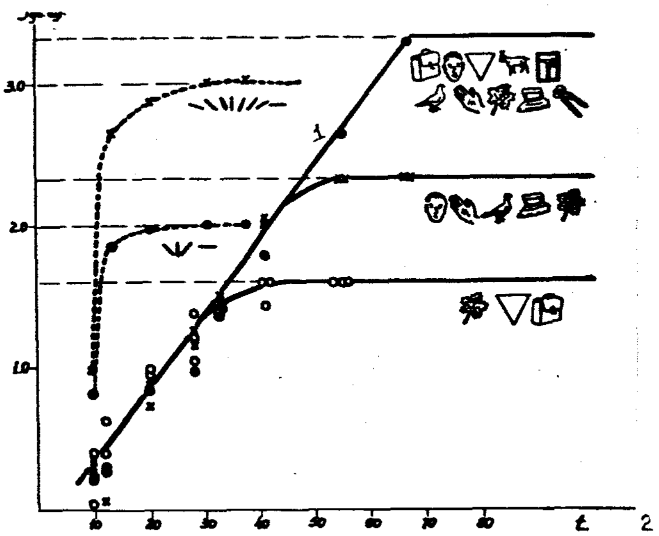

Fig. 5. Relationship between the amount of information obtained by an observer and the time required for processing the information in the visual system after recognition of variously oriented lines and pictures of objects. Size of image 4°.

1 - 49 binary digits/sec; 2 - msec

In recognizing sets of complex figures, the time required for a perfect performance is proportional to the number of figures that the observer was led to expect under the experimental conditions. The very fact that the time required for recognition varies with the size of the alphabet of possible images suggests that there are rearrangements is achieved only when the duration of the tones is lengthened to 400-500 msec.

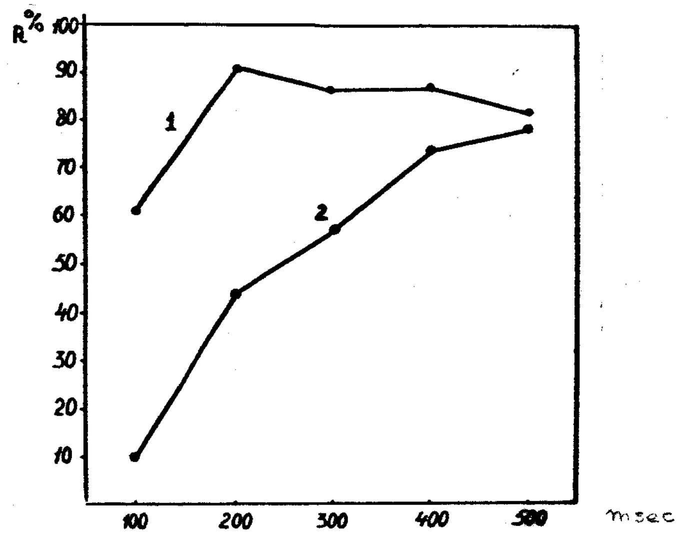

Fig. 6. Relationship between discrimination of 3-element sequences and duration of constituent sounds.

1 - sequences consisting of vowels (u, a, e);
2 - sequences consisting of tonal signals (150 cps, 500 cps, 1600 cps). Abscissa - duration of an element in a sequence; ordinate - amount of information received, calculated from the data from 15 listeners. Amount of information transmitted - 2.6 binary digits per sequence (choice of 6 different but equally probable sequences).

A remarkable feature of speech perception is the very rapid recoding of auditory images into motor articulatory images of audible sounds. This is particularly evidenced by the fact that man can repeat what he has heard after a very brief delay (120-150 msec). /18

There is reason to believe that the space occupied by the motor characteristics of the articulatory images is much smaller than that of the acoustic characteristics. Consequently, the change from continuous sound at the input of the auditory system to its description by a series of discrete motor images means that there is a very marked reduction of information, that the data are presented in a new and highly economical form.

Special experiments showed, however, that the size of the operational memory for a series of motor images likewise is not very large - about 7 syllables. This means that a person cannot remember a long sentence purely as a succession of syllables lacking in meaning. He must somehow turn to new elements of description which provide for an even more economical representation of the data. The experimental findings suggest that the next stage in information processing is identification and analysis of the word forms. A word form is remembered not as a /19 series of syllables or phonemes but as a set of grammatical and lexical characteristics describing the position of that word form among the possible word forms in the given language. In other words, this stage represents the shift from description of a communication in the space of the motor speech characteristics to its description in the space of the linguistic characteristics which reflect language rather than speech.

We should like to stress here that all this complexity in organizing speech perception is by no means excessive because it helps to overcome the difficulties attendant on processing sound information due to the limited size of the operational memory. This should be borne in mind by those attempting to create artificial "languages" of sound signal systems.

A method has been developed for the combined recording and measurement of articulatory parameters under the dynamic conditions of normal speech flow (Kozhevnikov, Chistovich et al.). A number of sensors are used for simultaneous and continuous recording of the following indices in the form of electric signals:

(1) Respiratory movements at different levels of the chest and abdomen;

(2) Intraoral pressure;

(3) Rate of air movement from the mouth;

(4) Rate of air movement from the nostrils;

(5) Lip movements;

(6) Lower jaw movements;

(7) Dynamic palatogram (dynamics of the tongue touching various parts of the hard palate);

(8) Vibrations of the vocal folds;

(9) Acoustic pattern in the nasal cavities;

(10) Normal acoustic pattern of speech recorded by a microphone;

(11) Electromyograms of several of the muscles involved in articulation.

Fig. 7 shows a subject with the principal sensors of the articulatory parameters.

The possibility of accurately comparing the time relations /20 between the various articulatory phenomena in the course of normal speech flow and the possibility of obtaining a sufficient mass of data for statistical purposes enabled us to conduct investigations aimed at determining: (a) the elements that make up the flow of speech, and (b) the general principles underlying the construction of a connected flow of speech from these elements. The main experimental material embraced a statistical study of the time pattern of articulation with changes in speech tempo, quantitative analysis of the phenomenon of artificially induced stammering during delayed acoustic feedback, observations on the effects of reduction and interstratification of individual articulatory phenomena, investigations of the characteristics of respiration during speech, and some other experiments. Space considerations prevent us setting forth all this material in our report, but we can express the following thoughts on the elements and principles involved in the organization of speech.

Fig. 7. Subject with the principal sensors of the articulatory parameters.

The sets of movements required to fashion syllables constitute the basic elements successively realized in the speech apparatus to create connected speech. A characteristic of Russian syllables (contrary to the prevalent linguistic view) is their openness, for they invariably end in a vowel. The coordination of movements within each syllable is complex. Effector instructions for articulatory ~~realization~~ execution of the syllable program are supplied with a considerable overlapping in time and only essentially antagonistic movements are performed in strict succession. The coordination of movements of the speech organs that make up the syllable, as might be expected, is accomplished chiefly at the lowest levels of the nervous system. The syllable may be regarded, therefore, as a kind of "unit" containing a definite part of the speech synthesis program.

In connected speech the syllables are combined into larger units /21 of "physiological organization" of the speech flow - syntagmas. A syntagma can be identified because of a peculiarity of speech respiration. In articulating a syntagma, intrapulmonary pressure is continuously maintained; inspiration is possible only between syntagmas. A syntagma is thus a rather long segment of a program that controls speech synthesis. It embodies a sequence of syllables uttered in a complex rhythm. Fig. 8 is a diagram of the principal operations carried out during the synthesis of syllables and syntagmas in oral speech.

The data obtained from our investigation of the dynamics of articulatory movements in the flow of speech warrant the following assumption. The change from the succession of phonemic symbols that describes the sentence program at the highest levels of speech control to the succession of articulatory movements includes the breakdown of the series of phonemes into groups, each of which ends in a vowel. The groups of symbols are supplied one after the other to the input of the motor system proper and used for the synthesis or selection of the appropriate articulatory complex. This ensures an extremely high rate of creating information by means of speech.

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Fig. 8. Diagram of operations performed during the synthesis of syllables and syntagmas.

A - syntagma program unit; B_1, B_2...B_n - syllable program units; C - articulatory movements ("actuating elements"); a - "trigger signal"of syntagma; b_1, b_2...b_3 - "trigger signals" of syllables; c'_1, c'_2...c'_n - "trigger signals" of articulatory movements; d_1, d_2... - correction signals of syllable program.

Naturally, this method of solving the problem of accelerating the /22 rate of transmission of information is feasible only if the number of muscle groups participating in the creation of complexes is sufficiently large and the set of instructions for them (i.e., the number of distinguishable articulatory complexes) is very great. There are several thousand different syllables. Also, the coordination of movements within a complex has to be very precise, as in speech.

In the light of the foregoing, it is not realistic to assume that a new artificial system of movements can be devised to provide the same rate of transmission of information as in movements of the speech organs. Then too there is a remarkable coincidence of the capacities of the visual system and the speech apparatus (50 binary digits per second), which testifies to the existence of good quantitative agreement in processed information as between the "input" and "output" of the nervous system. Voice communication is clearly the most promising method of transmitting information from the astronaut to the machines. This means that investigators must concentrate on developing devices for automatic speech recognition.